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Content of Chemical Elements in Tree Rings of Lodgepole Pine and Whitebark Pine from a Subalpine Sierra Nevada Forest

David L. Peterson **Darren R. Anderson**

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The wood of lodgepole pines and whitebark pines from a high elevation site in the east-central Sierra Nevada of California was analyzed for chemical content to determine whether there were any temporal patterns of chemical distribution in tree rings. Cores were taken from 10 trees of each species and divided into 5-year increments for chemical analysis. Correlation analysis indicated that calcium and magnesium, both of which have divalent cations, were strongly correlated for both species. The elements copper, iron, cobalt, nickel, molybdenum, chromium, tin, and arsenic were all significantly correlated with one another in lodgepole pine but not in whitebark pine. Concentrations of calcium and magnesium decreased over time for both species, while that of boron increased dramatically. None of the other elements showed significant trends. Most elements had higher concentrations in the youngest wood, which probably reflects greater mobility of soluble forms of elements in and adjacent to living vascular tissue. Chemical concentrations in the wood of trees from this study are presumably free of the effects of substantial input from humans. This data set therefore provides valuable information on wood chemistry with which to evaluate disturbed or polluted stands with similar characteristics.

Retrieval Terms: dendroecology, tree growth, wood chemistry

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IN BRIEF . . .

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Retrieval Terms: dendroecology, tree growth, wood chemistry

Little is known about the ecology of high-elevation forests in the Sierra Nevada of California. Tree species located near timberline grow slowly and may be sensitive to small environmental changes. The effects of atmospheric deposition on California forests are of particular concern because of the presence of phytotoxic levels of ozone and elevated levels of nitrogen deposition at some montane locations. In addition, some high elevation sites are poorly buffered against potential increases in the acidity of precipitation and snowmelt.

Some studies have indicated that the chemical content of wood can be used to detect changes in the atmospheric environment and other factors over time. Chemical analysis of cores has been particularly useful in studies of trees located adjacent to smelters and industrial operations, but has been less successful in identifying chemical markers in trees exposed to nonpoint sources of pollution.

In this study, cores of lodgepole pine and whitebark pine were analyzed for chemical content to determine whether there were any temporal patterns of chemical distribution in tree rings. Trees were sampled above 3000 m near timberline in the Sierra Nevada of California, at a location that is assumed to have minimal human disturbance or impact from air pollutants. Trees of a wide range of sizes and ages of both species were sampled.

Calcium and magnesium (both divalent cations) were strongly correlated with each other in both species. Copper, iron, cobalt, nickel, molybdenum, chromium, tin, and arsenic were all correlated with each other in lodgepole pine but not whitebark pine. The clearest trends in the data were decreases in calcium and magnesium over time, and a dramatic increase in boron. These trends were found in both species. In addition, most elements had higher concentrations in the youngest wood, which probably indicates greater mobility of soluble forms of elements adjacent to living vascular tissue. There was a high degree of variance in chemical concentration data.

This data set provides information on wood chemistry from a site without the influence of human disturbance or elevated levels of pollutants. The data can therefore be compared with those from similar sites that may be affected by pollutants, in order to determine whether a chemical marker related to air pollution can be detected. The data can also serve as a bench mark for future evaluations of tree growth and chemical content of wood at the study site.

INTRODUCTION

High-elevation forest ecosystems of the Sierra Nevada of California may be sensitive to small environmental changes. Trees at high elevations grow slowly, and species near timberline are at the limit of their existence due to low temperatures and desiccation. Subalpine forests may be affected by atmospheric deposition as well as by changes in atmospheric CO_2 (Bazzaz and others 1985, Oechel and Strain 1985). It is impossible to determine whether there are changes in the ecosystem, however, without a record through time. The expected range of variability in ecosystem response to environmental variables must also be known.

Lodgepole pine *(Pinus contorta* var. *murrayana)* and whitebark pine *(Pinus albicaulis)* are common species in the subalpine forests of the Sierra Nevada. Research has been conducted on the ecology and silviculture of lodgepole pine (e.g., Lotan and Perry 1983), although there is little information on this species in California. There have been a few studies on the ecology of whitebark pine (Arno and Hoff 1989, Forcella and Weaver 1977, Peterson and Arbaugh 1990, Weaver and Dale 1974), including recent work on its physiology (Armstrong and others 1988) and leaf area (Peterson and others 1989). Previous ecological studies of high elevation forests in California have focused on red fir *(Abies magnifica)* (Oosting and Billings 1943, Westman 1987).

Previous dendroecological studies have indicated that chemical content of wood can be used in some cases to identify changes in the atmospheric environment over time (Bräker and others 1985, Lepp 1975). A number of studies have identified changes in the concentration of some elements over time that are related to differing exposures to pollutants from industrial processes (Arp and Manasc 1988, Baes and McLaughlin 1984, Guyette and McGinnes 1987) or to site and soil characteristics (McClenahen and others 1987, 1989). It has been considerably more difficult to associate chemical distribution in tree rings with regional effects of atmospheric deposition (Berish and Ragsdale 1985, Frelich and others 1989, Legge and others 1984). A reliable baseline is needed to compare trees with potential effects of chemical changes. Analyses of chemical content of wood from areas free of pollution may help to determine whether there have been chemical changes in trees at similar sites.

This paper reports the results of a study to analyze the chemical content of lodgepole pine and whitebark pine cores from a subalpine Sierra Nevada forest, to determine whether there were any temporal patterns of chemical distribution in tree rings.

METHODS

The study site was located in the Eastern Brook Lakes watershed at 118°44' W. longitude, 37°26' N. latitude in the Inyo National Forest, Inyo County, California. This high-elevation forest is relatively free of air pollutants and has no history of large-scale human disturbance. The 250-ha watershed is located between 3170 and 3780 m elevation and contains lodgepole pine and whitebark pine forest, alpine meadows, willows *(Salix* spp.), and scattered shrubs. A large portion of the watershed consists of a lake, several streams, granite cliffs, and talus slopes. There is little evidence of fire in the watershed. Frequent avalanches appear to be the major form of disturbance. Soils within the sample area are of a glacial origin and derived from granitic material. They are classified as Typic Cryochrepts, and depth to bedrock is less than 100 cm (B. Smith unpublished data).

The sampling area was composed of mixed lodgepole pine and whitebark pine (Peterson and Arbaugh 1990, Peterson and others 1989). Slope was less than 10 percent in this area, with little variation in slope or other site characteristics. Density was 3050 stems/ha, and basal area was 18.2 m²/ha (Peterson and others 1989). Ten trees of each species *(table 1)* were sampled along a transect using the point-centered quarter method (Peterson and Arbaugh 1990). All trees exceeded 10 cm in diameter without major crown or stem defects. Trees were cored with an

Table 1—*Summary of characteristics of sample trees*

Core no.	D.b.h.[1]	Height	Beginning year of core
	cm	*m*	
Lodgepole pine			
1	12.0	5.0	1972
2	24.0	7.0	1887
3	41.5	9.5	1827
4	31.0	9.0	1857
5	41.0	17.0	1852
6	20.0	11.5	1897
7	54.5	19.0	1897
8	15.0	10.5	1932
9	25.5	9.0	1942
10	10.5	4.5	1942
Whitebark pine			
1	10.0	7.0	1913
2	8.5	6.0	1928
3	12.0	12.0	1928
4	11.5	7.0	1903
5	14.5	8.5	1868
6	37.0	15.0	1823
7	21.5	13.0	1843
8	17.5	12.5	1873
9	12.0	7.0	1918
10	30.5	14.0	1818

[1]D.b.h. is diameter at breast height.

increment borer, with one core being taken from one of the cross-slope positions of each tree. Cores were stored in paper straws and transported back to the laboratory for analysis.

Cores were sanded as necessary so that individual rings were clearly visible. They were then crossdated (Fritts 1976) so that individual rings could be associated with specific years. Tree cores were then sectioned into 5-year increments for chemical analysis. Each 5-year increment was placed in a separate sample vial and submitted for laboratory analysis. Wood samples were analyzed by the chemical analysis laboratory of the Department of Biological Science at the University of California, Los Angeles, by using inductively coupled plasma emission spectroscopy after ashing and dissolving samples in nitric acid. Total concentration of the following elements was determined: phosphorus (P), sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), boron (B), silicon (Si), titanium (Ti), vanadium (V), cobalt (Co), nickel (Ni), molybdenum (Mo), chromium (Cr), strontium (Sr), barium (Ba), silver (Ag), tin (Sn), lead (Pb), arsenic (As), cadmium (Cd), beryllium (Be), lithium (Li).

Correlation analysis (Pearson product-moment correlation coefficient) was initially conducted to determine the relationship between pairs of elements. The entire time series of all cores for each species were used to calculate correlation coefficients. Concentration of elements over time was plotted for each element of each tree core. These graphs were aggregated for display purposes.

RESULTS AND DISCUSSION

Correlation Analysis

Distributions of chemical elements in the wood of lodgepole pine and whitebark pine varied widely, and trends were difficult

Table 2–*Mean of Pearson product-moment correlation coefficients for elements in 10 lodgepole pine cores. Correlation coefficients are for all time segments of all cores (n=). Values greater than 0.5000 are underscored to assist the reader in locating large values.*

	P	NA	K	CA	MG	ZN	CU	FE	MN	B	A	SI	TI	V	CO	NI	MO	CR	SR	BA	LI	AG	SN	PB	BE	CD	AS
P	1.000																										
NA	.350	1.000																									
K	.165	-.017	1.000																								
CA	.212	.048	.148	1.000																							
MG	.272	.076	.181	.760	1.000																						
ZN	.221	.097	.328	.239	.307	1.000																					
CU	.685	.329	.059	.143	.198	.131	1.000																				
FE	.821	.383	.033	.117	.151	.166	.715	1.000																			
MN	.361	.193	.042	.536	.431	.384	.202	.353	1.000																		
B	.238	.144	.481	.092	.046	.260	.056	.213	.142	1.000																	
AL	.400	.245	.346	.141	.221	.361	.269	.452	.249	.458	1.000																
SI	.367	.319	.159	.028	.097	.328	.247	.439	.296	.328	.737	1.000															
TI	-.055	-.045	-.067	-.007	-.023	-.090	.034	-.021	-.163	-.106	.103	.005	1.000														
V	-.425	-.216	.119	-.433	-.468	-.062	-.353	-.326	-.295	-.010	-.041	-.104	.126	1.000													
CO	.719	.425	.087	.069	.084	.060	.773	.863	.239	.144	.242	.230	.003	.280	1.000												
NI	.757	.318	.017	.164	.175	.091	.843	.812	.262	.148	.276	.260	-.090	-.425	.900	1.000											
MO	.677	.379	-.100	.206	.198	.125	.729	.674	.269	.166	.222	.231	-.110	-.528	.809	.816	1.000										
CR	.809	.403	.029	.320	.322	.161	.736	.792	.380	.230	.341	.295	-.036	-.499	.782	.837	.802	1.000									
SR	.358	.203	.273	.846	.773	.264	.273	.290	.530	.358	.351	.200	-.030	-.457	.222	.304	.353	.492	1.000								
BA	.406	.224	.227	.805	.744	.276	.259	.290	.464	.324	.338	.175	-.037	-.419	.227	.281	.358	.453	.887	1.000							
LI	.236	.121	-.200	-.042	.085	-.229	.149	.238	-.030	-.174	-.054	-.195	-.058	.328	.193	-.100	-.133	-.097	.009	.170	1.000						
AG	-.221	-.029	-.173	-.208	-.299	-.056	-.225	-.260	-.064	-.130	-.200	-.189	.111	.360	-.146	-.304	-.128	-.205	-.305	-.222	.234	1.000					
SN	.540	.398	-.119	.023	.032	-.059	.511	.548	.226	.138	.166	.231	-.074	-.357	.591	.578	.623	.526	.175	.146	.052	.031	1.000				
PB	.420	.292	.009	.521	.478	.141	.265	.328	.436	.302	.184	.140	-.190	-.445	.393	.421	.562	.591	.639	.631	-.134	.016	.487	1.000			
BE	-.278	-.162	-.161	.053	-.053	-.119	-.428	-.549	-.092	-.152	-.371	-.331	-.042	.027	-.526	-.425	-.223	-.288	-.082	-.019	.089	.492	-.093	.191	1.000		
CD	-.350	-.166	-.078	-.491	.443	.154	-.301	-.280	-.432	-.290	-.221	-.127	.074	.357	-.222	-.284	-.276	-.310	-.605	-.597	-.068	.015	-.257	-.352	.002	1.000	
AS	.609	.389	.098	-.042	-.096	.125	.582	.601	.179	.192	.241	.272	.021	-.157	.623	.624	.646	.643	.108	.109	-.153	.190	.715	.428	-.079	-.130	1.000

	P	NA	K	CA	MG	ZN	CU	FE	MN	B	A	SI	TI	V	CO	NI	MO	CR	SR	BA	LI	AG	SN	PB	BE	CD	AS
P	1.000																										
NA	.454	1.000																									
K	.527	.216	1.000																								
CA	.228	.036	.560	1.000																							
MG	-.023	-.157	.342	.824	1.000																						
ZN	.573	.304	.586	.562	.345	1.000																					
CU	.211	.222	.225	.272	.176	.321	1.000																				
FE	.572	.206	.123	.114	-.029	.255	.002	1.000																			
MN	.301	.027	.378	.675	.636	.469	.196	.144	1.000																		
B	.429	.248	.537	.263	.018	.456	.056	.458	.241	1.000																	
AL	.478	.299	.583	.549	.307	.581	.347	.483	.329	.627	1.000																
SI	.314	.249	.055	.006	-.116	.164	-.098	.622	-.014	.456	.520	1.000															
TI	-.118	.253	-.184	.073	.141	-.060	.107	-.154	-.077	-.277	-.020	-.083	1.000														
V	.187	.122	.068	-.192	-.315	.003	.112	-.039	-.064	-.136	-.204	-.116	-.090	1.000													
CO	.016	.156	-.154	-.379	-.383	-.194	-.008	-.189	-.285	-.157	-.087	-.063	.272	.103	1.000												
NI	.239	.203	-.002	-.087	-.184	.061	.059	.230	-.059	.174	.148	.143	-.019	-.021	.178	1.000											
MO	.347	.531	.002	-.120	-.246	.172	.019	.211	-.002	.235	.198	.204	.008	.083	.326	.308	1.000										
CR	.361	.066	.113	.228	.200	.202	.234	.535	.212	.099	.200	.141	.032	.053	-.123	.107	.058	1.000									
SR	.360	.130	.674	.850	.685	.626	.323	.257	.641	.420	.610	.105	.004	-.064	-.380	-.021	-.044	.403	1.000								
BA	.253	.153	.589	.897	.754	.576	.283	.158	.665	.356	.620	.097	.134	-.197	-.317	-.067	-.004	.238	.871	1.000							
LI	.352	.261	-.269	.089	.025	.019	.476	.440	.039	-.225	.041	.137	.110	.533	-.064	-.062	.222	.561	.096	.021	1.00						
AG	.144	.297	.092	-.258	-.358	-.011	-.102	-.260	-.190	.052	-.138	-.106	.028	.257	.567	.019	.320	-.312	-.274	-.231	-.346	1.000					
SN	.242	.468	.094	-.042	-.111	.179	.002	-.024	.028	.006	-.033	.047	.093	.183	.098	.007	.256	-.142	-.028	-.035	-.368	.373	1.000				
PB	-.068	.064	.263	.307	.284	.265	-.214	.055	.244	.532	.275	.186	.277	-.201	-.172	-.083	.071	-.175	.280	.319	-.417	.161	.162	1.000			
BE	-.122	-.019	.127	-.073	-.069	.034	-.076	-.609	-.062	-.074	-.289	-.415	-.103	.219	.112	-.154	-.038	-.507	-.152	-.108	-.365	.526	.297	.326	1.000		
CD	.227	.196	-.044	-.267	-.408	.116	-.124	-.111	-.305	-.148	-.133	-.098	-.008	.329	.222	-.086	.197	-.176	-.306	-.335	.000	.448	.377	-.153	.401	1.000	
AS	.402	.407	.141	-.308	-.478	.170	-.024	-.084	-.181	.042	-.108	-.036	-.063	.338	.341	.048	.340	-.258	-.256	-.269	-.276	.698	.512	.026	.494	.565	1.000

Table 3–*Mean of Pearson product-moment correlation coefficients for elements in 10 whitebark pine cores. Correlation coefficients are for all time segments of all cores (n=). Values greater than 0.5000 are underscored to assist the reader in locating large values.*

to interpret in some cases. Unfortunately this is typical in most studies of this type because natural variation is high and the relationship between element concentration and the environment of trees is complex.

Correlation analysis indicated correlations among certain groups of elements *(tables 2, 3)*. Statistical significance is not indicated in the tables, although correlation coefficient values greater than 0.5 and less than -0.5 have been underscored. One of the strongest average correlations for both species was between Ca and Mg. Both elements are relatively abundant in most soils, are critical for plant nutrition, and are divalent cations in solution. Both Ca and Mg are also correlated with the divalent cations Ba and Sr in both species. Ba and Sr are highly correlated with each other in both species, and are both correlated with K, Zn, Mn, and Al in whitebark pine but not in lodgepole pine. Al and Si, both common elements in the structure of clay minerals, were correlated in both species.

Correlations among some of the metals were found for lodgepole pine but not for whitebark pine. Cu, Fe, Co, Ni, Mo, Cr, Sn, and As were all correlated with one another *(table 3)*. In addition, all eight elements were correlated with P.

Some of the correlations were expected on the basis of simple chemical principles *(tables 2, 3)*. For example, one might expect Ca and Mg to have directly proportional concentrations in wood because they are both relatively common divalent cations. Correlations of these elements with their chemical analogs, Ba and Sr, are also to be expected. Correlations among some of the metals are reasonable because they have similar adsorption and transport mechanisms in plants (Lepp 1975). It is not clear, however, why there was such a large discrepancy between tree species.

Temporal Trends in Element Concentration

The time series of chemical concentrations in the wood of whitebark pine and lodgepole pine must be interpreted in the context of radial growth patterns of the trees. Basal area trends for the Eastern Brook Lakes study site were described in a previous study (Peterson and Arbaugh 1990), which determined that basal area growth increased over time for all age classes of both species. This is an unusual pattern of growth for most conifers, which normally have a plateau or reduction in annual basal area increment after 50-100 years.

Figures 1-10, which depict temporal trends, present data for all cores. The figures are rather "noisy," but are valuable because they display the entire range of element concentrations for trees of different ages. There are several high or low values for some elements, probably due to errors in chemical analysis, values outside the detection limits of the instrument used for analysis, or sample contamination. The overall trend of element concentrations should be observed, rather than these outliers.

Phosphorus *(fig. 1)*

P concentration for half of the whitebark pines increased slightly, especially since 1950. Except for a recent increase in some trees, no apparent trend was found in lodgepole pine. The data contained a high degree of variance. Similar studies of red spruce *(Picea rubens)* (Arp and Manasc 1988), Eastern white pine *(Pinus strobus)*, and sugar maple *(Acer saccharum)* (Frelich and others 1989) showed no increase in P concentration over time, except in the youngest wood.

Phosphorus is an important structural component of many plant compounds, especially nucleic acids and phospholipids, and plays a critical role in energy metabolism (Bidwell 1974). The high levels of P found in the youngest wood in this and other studies is probably related to the process of wood formation, which leaves substantial concentrations of P in newly formed xylem. Concentrations may be reduced in subsequent years by the radial flow of sap through the stems (Arp and Manasc 1988).

Potassium *(fig. 2)*

No trend in K concentration was found for either species, although concentration was much higher during the most recent 10 years of growth. The concentration for the youngest increment of wood was twice that of wood that was 10 years older in both species. Variance in concentration was generally higher in whitebark pine than in lodgepole pine. This pattern was similar to that found in other tree species (Arp and Manasc 1988, Frelich and others 1989, Matusiewicz and Barnes 1985).

Potassium has no structural role in plants, but serves in a number of catalytic roles. It is apparently involved in enzyme activity, especially for protein synthesis (Bidwell 1974). It also serves as an osmotic agent in the opening and closing of stomata (Kramer and Kozlowski 1979). It is highly mobile in plants and is easily translocated among different tissue types in trees (Peterson and Rolfe 1982). The high concentrations of K found in the youngest wood are probably related to the process of wood formation, with reduction in subsequent years by radial sap movement (Arp and Manasc 1988).

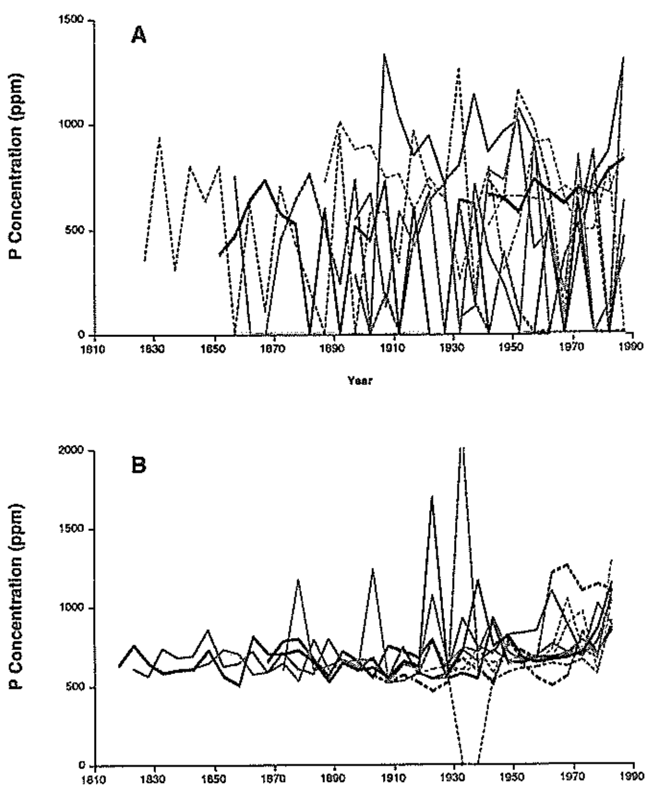

Figure 1—Concentration of P (ppm) over time for lodgepole pine (A) and whitebark pine (B). Each line represents a separate tree core. Colors and type of line were randomly assigned to each tree, and are consistent among all figures (for example, the same tree is represented by a solid red line in *figs. 1-10*).

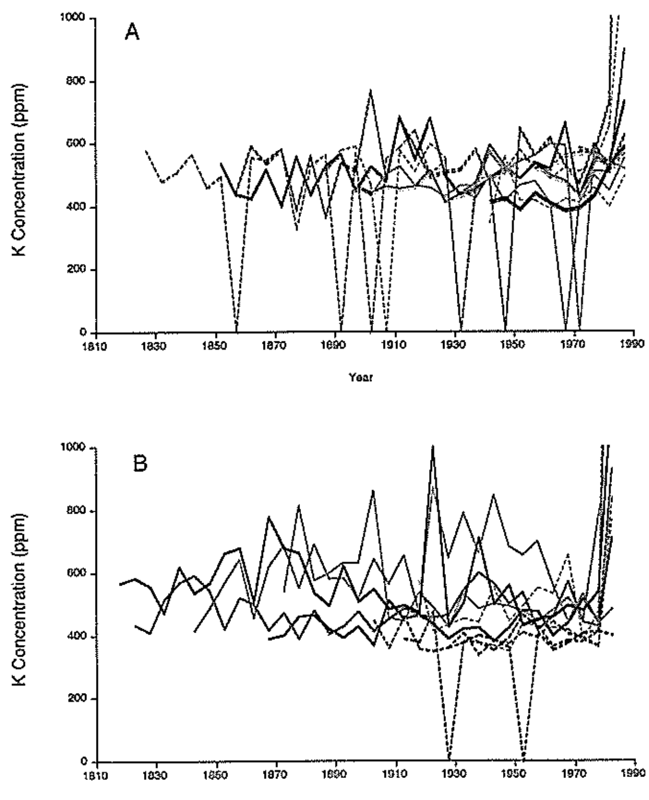

Figure 2—Concentration of K (ppm) over time for lodgepole pine (A) and whitebark pine (B). Each line represents a separate tree core.

Calcium *(fig. 3)*

Concentration of Ca decreased through time for both species, in older as well as younger trees. Concentrations during the most recent 5 years were high for whitebark pine and slightly higher than the previous 5-year increment in lodgepole pine. Concentrations of Ca in the 1970's was about half that of the oldest wood in many cores of both species. The pattern of decreasing Ca through time is similar to that found in other species (Arp and Manasc 1988, Frelich and others 1989, Meisch and others 1986), although the high concentration in the youngest wood is different. Although Ca concentration decreased over time, the absolute amount of Ca fixed in the wood may be relatively constant because of the concurrent increase in basal area increment (Peterson and Arbaugh 1990).

Calcium is a critical element in plants and is found in high concentrations in most plants and soils. It is important in the synthesis of pectin in the middle lamella of cell walls, is involved in the metabolism of the nucleus and mitochondria (Bidwell 1974), is an enzyme activator, and is involved in nitrogen metabolism (Kramer and Kozlowski 1979). Calcium is generally regarded as an immobile element because it is fixed in xylem cell walls and incorporated into woody tissue. However, the high concentrations of Ca in the youngest wood of the trees in our study suggest that there must be some mobility in order to reduce these concentrations as the wood ages.

Magnesium *(fig. 4)*

The overall trend of Mg concentrations paralleled that of Ca for younger and older trees of both species. Concentrations in the 1970's were half that of the oldest wood in the core for lodgepole pine and 20-30 percent of the oldest wood in some whitebark pine cores. Concentrations during the most recent 5 years were several times higher than the previous 5-year increment for whitebark pine and slightly higher in most lodgepole pines. The generally decreasing trend in Mg again paralleled that of other species (Arp and Manasc 1988, Frelich and others 1989, Matusiewicz and Barnes 1985), but the high concentrations in the youngest wood was a major difference.

Magnesium is critical for several plant functions. It is a constituent of the chlorophyll molecule, is involved in the phosphate transfer reaction of several enzyme systems, and is involved in maintaining the integrity of ribosomes (Kramer and Kozlowski 1979). Magnesium is highly soluble and readily transported within plants, and concentrations tend to be high in xylem sap (Stark and others 1984). These factors may account for the high concentration of Mg found in this study and the reduction in concentration as the wood ages.

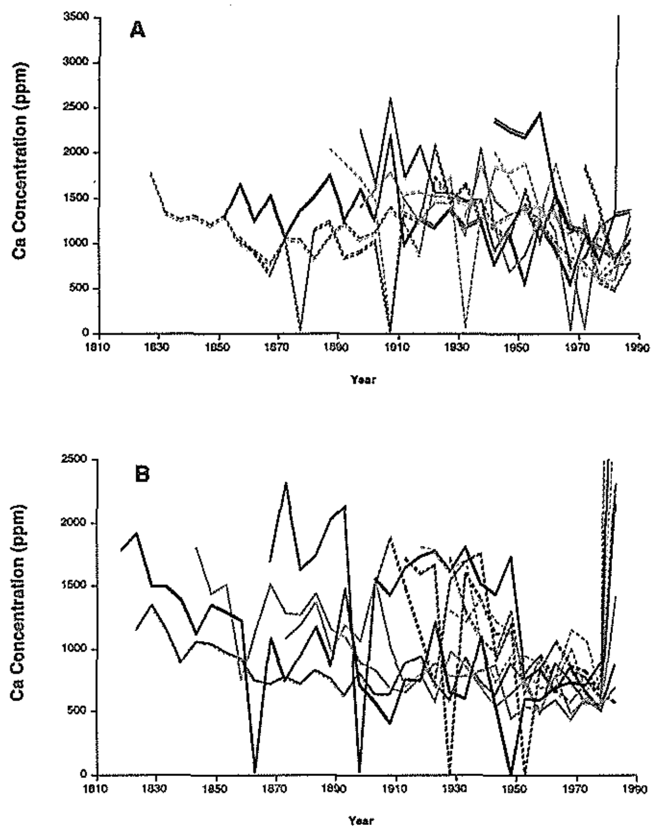

Figure 3—Concentration of Ca (ppm) over time for lodgepole pine (A) and whitebark pine (B). Each line represents a separate tree core.

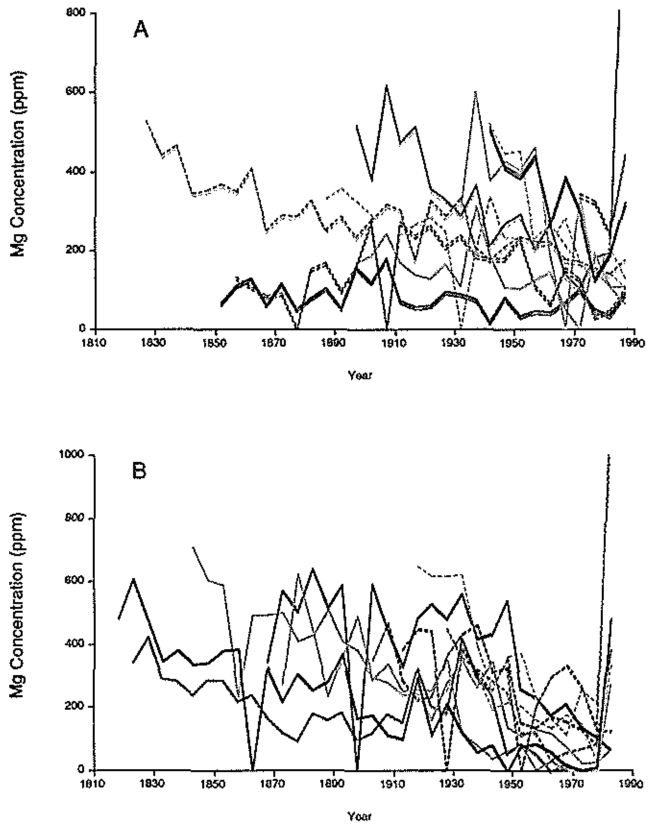

Figure 4—Concentration of Mg (ppm) over time for lodgepole pine (A) and whitebark pine (B). Each line represents a separate tree core.

Sodium *(fig. 5)*

Concentrations of Na tended to increase in about 1930 and decrease in 1950 for about half of the lodgepole pine cores. We found no apparent trend for whitebark pine. The pattern was quite different from the general decreasing trend found in red spruce (Matusiewicz and Barnes 1985). Sodium has no apparent function in plants other than halophytes, and the patterns found in this study are difficult to explain. The temporary increase found in this study may be related to increased availability of Na in the soils due to drying. Sodium concentrations probably contain little information about nutrition in conifers, although they can reflect changes in uptake patterns.

Boron *(fig. 6)*

Concentrations of B increased over time for both species, and concentration of the youngest wood was several times higher than that of the oldest wood in several cores. This increase was especially prominent since 1960, with highest values during the most recent time period. Concentrations were quite similar for both species. The increase in B, coupled with the temporal increase in basal area increment for most cores, indicates that there was a substantial increase in the amount of B fixed in the wood over time.

Boron is essential in small quantities for plant growth, although its role in plant metabolism is poorly understood. It appears to be involved in the translocation and absorption of sugars in plants (Bidwell 1974). Conifers tend to be more tolerant than angiosperms of lower concentrations of B, and normally have specific requirements for less than 15 ppm (Kramer and Kozlowski 1979). Many of the trees in this study accumulated concentrations higher than 15 ppm. We could not find similar studies of B distribution in wood in the literature. The increasing concentration of B over time is difficult to explain, although it is possible that salts containing B increased in the soil over time because of drying and became increasingly available for uptake.

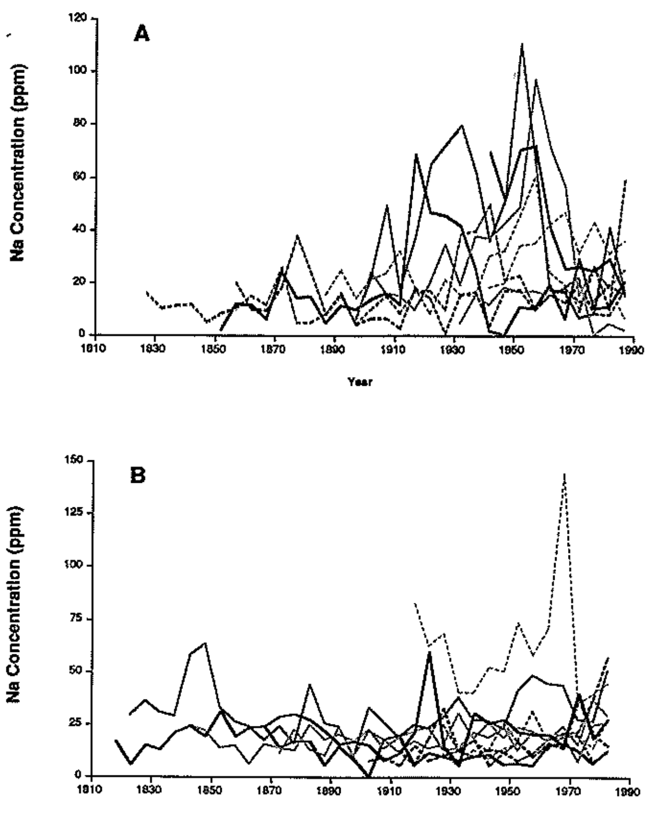

Figure 5—Concentration of Na (ppm) over time for lodgepole pine (A) and whitebark pine (B). Each line represents a separate tree core.

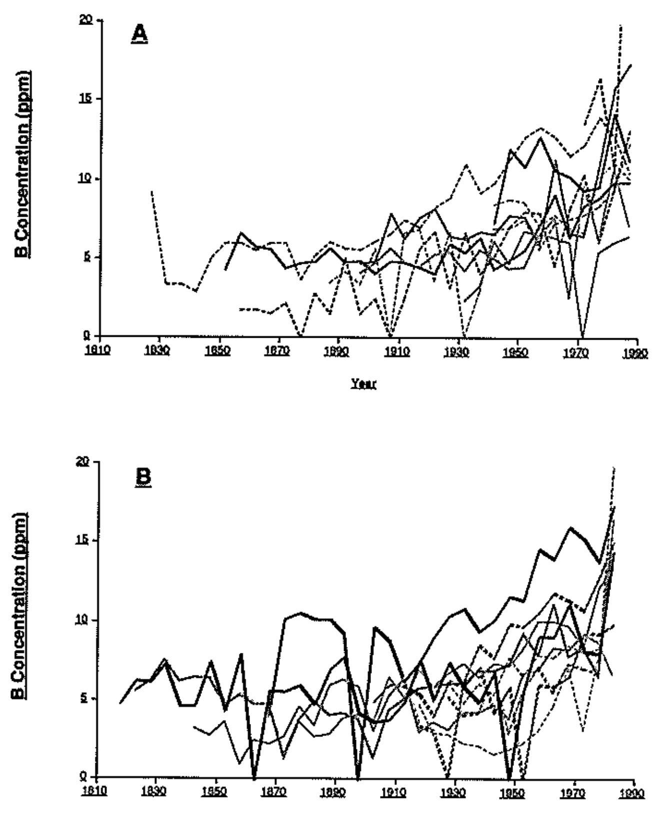

Figure 6—Concentration of B (ppm) over time for lodgepole pine (A) and whitebark pine (B). Each line represents a separate tree core.

Iron *(fig. 7)*

The trend in Fe concentration was weak, although some whitebark pines appeared to have a slightly increasing trend in Fe concentration since 1960. This generally agrees with the results of other studies (Frelich and others 1989), although red spruce had a much longer period of concentration increase (Arp and Manasc 1988, Matusiewicz and Barnes 1985).

More iron is required in plants than are other micronutrients, probably because of its low solubility. Fe is part of the catalytic site of important oxidation-reduction enzymes, and is essential for chlorophyll synthesis (Bidwell 1974). The higher recent concentrations of Fe in some trees indicate that there is some mobility of this element in wood despite its low solubility.

Copper *(fig. 8)*

No trend in Cu concentrations for either species was detected. Concentrations tended to be higher and more variable in lodgepole pine than in whitebark pine. The low concentrations and lack of trend agree with studies of other species from nonpolluted sites (Arp and Manasc 1988, Berish and Ragsdale 1985, Matusiewicz and Barnes 1985, Robitaille 1981).

Copper is generally found in small quantities in both soils and plants. It plays a catalytic role in plants as part of a number of important enzymes, and is present in plastocyanin in chloroplasts (Bidwell 1974). Concentrations measured in this study were low and far below the range considered to be indicative of contamination from industrial processes (Arp and Manasc 1988, Robitaille 1981).

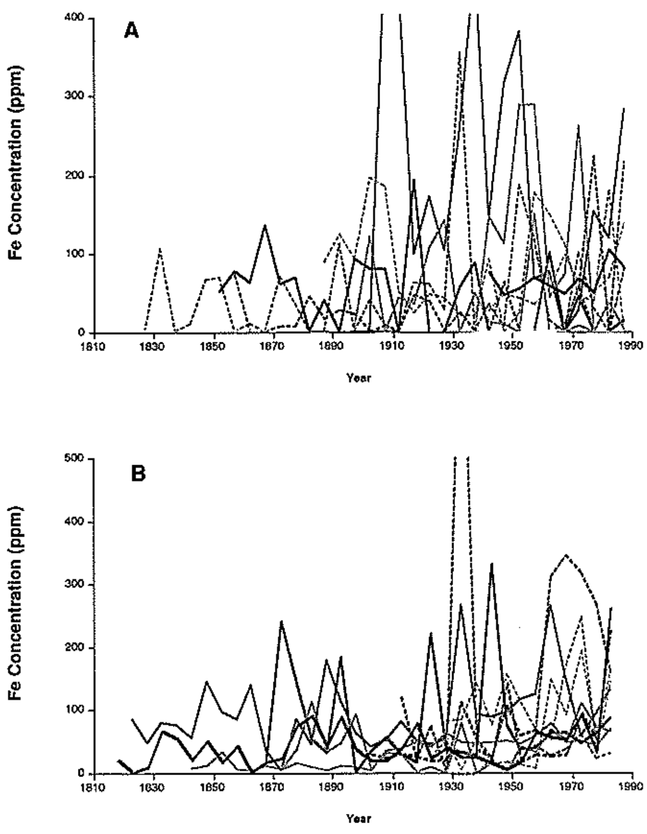

Figure 7—Concentration of Fe (ppm) over time for lodgepole pine (A) and whitebark pine (B). Each line represents a separate tree core.

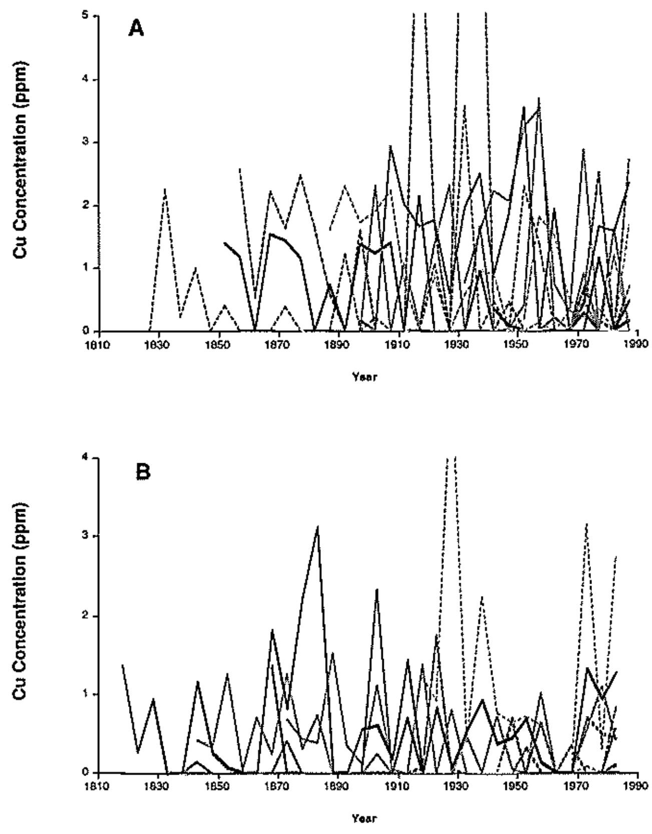

Figure 8—Concentration of Cu (ppm) over time for lodgepole pine (A) and whitebark pine (B). Each line represents a separate tree core.

Manganese *(fig. 9)*

No trend in Mn concentrations for either species was detected. Some of the whitebark pine cores had a large increase in Mn concentration during the most recent 5-year increment. Previous studies that evaluated Mn concentration also found no temporal trends at unpolluted sites (Arp and Manasc 1988, Berish and Ragsdale 1985, Matusiewicz and Barnes 1985), but none of these studies had the high concentations found in the most recent whitebark pine wood. Younger trees of both species tended to have higher Mn concentrations, which agrees with previous results for red spruce (Arp and Manasc 1988).

Manganese is widely involved in catalytic roles in plants. It is an important enzyme activator in the Krebs cycle and is required in other respiratory processes, nitrogen metabolism, and photosynthesis. It may also have a structural role in chloroplasts (Bidwell 1974) and affect the availability of Fe (Kramer and Kozlowski 1979). The lack of trend in this study indicates that there has probably been no unusual deposition of Mn in the watershed.

Zinc *(fig. 10)*

No trend in concentrations for either species was detected. Most of the whitebark pines and half of the lodgepole pines had a large increase during the most recent 5-year increment. There was a range of results for previous studies of Zn concentrations in trees, including decreasing temporal trend (Arp and Manasc 1988, Robitaille 1981), increasing trend (Berish and Ragsdale 1985), and no trend (Frelich and others 1989, Matusiewicz and Barnes 1985). None of these studies found the high Zn concentrations that we observed in the youngest wood of whitebark pine.

Zinc is involved in the synthesis of indoleacetic acid and is therefore related to the form and growth habit of plants. Zinc is also an activator of several important enzymes, and is involved in protein synthesis (Bidwell 1974). The lack of trend in Zn concentration suggests that this metal did not cause any contamination at the study site.

Lead, Tin, Barium, Strontium

Concentrations of Pb, Ba, and Sr decreased in most lodgepole pine cores since 1940 and Sn decreased since 1950. Similar trends were found in whitebark pine. None of these elements has a known function in plants, but are discussed here because they displayed some trends in the concentration data. Lead is of particular interest because it is a common pollutant associated with gasoline and is phytotoxic. Concentrations measured in this study were too low to reflect the possible effect of automobile emissions (Rolfe 1974) or a change from the use of leaded to unleaded fuel. The only other study that examined Ba and Sr

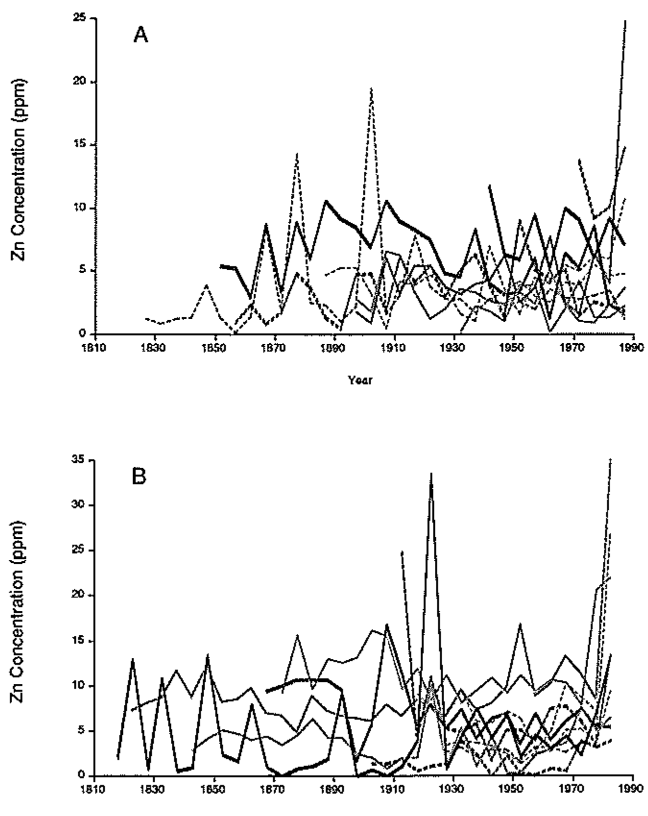

Figure 9—Concentration of Mn (ppm) over time for lodgepole pine (A) and whitebark pine (B). Each line represents a separate tree core.

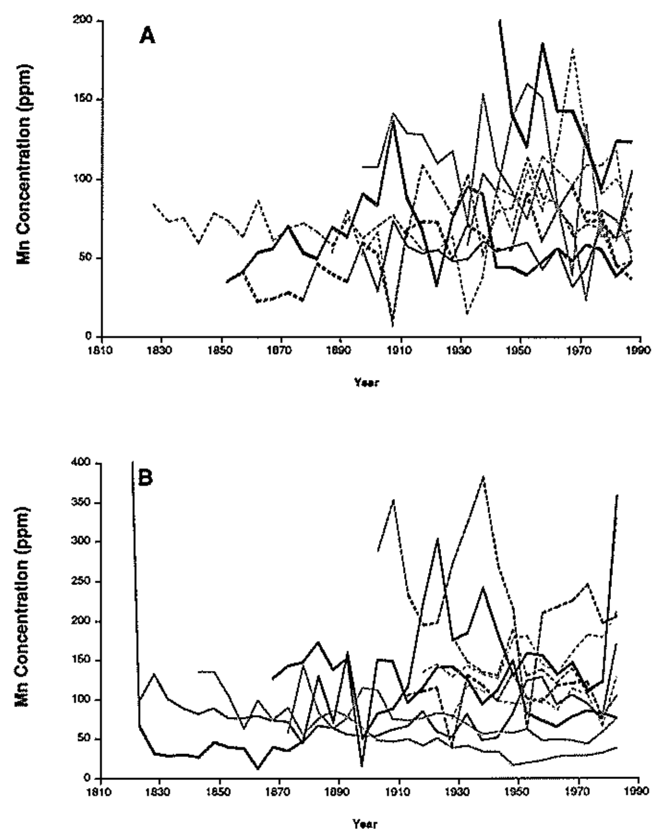

Figure 10—Concentration of Zn (ppm) over time for lodgepole pine (A) and whitebark pine (B). Each line represents a separate tree core.

concentrations found no trend (Matusiewicz and Barnes 1985), and no studies could be located that evaluated Sn.

Aluminum, Silicon

Neither Al nor Si has a known function in plant growth, but each is normally found in moderately high concentrations in plants (Kramer and Kozlowski 1979). We detected no trends in the concentrations of Al and Si, although Al concentrations were very high (25-50 ppm) during the most recent 5-year increment compared to the previous portion of the time series (0-20 ppm). Previous studies also found a recent increase in Al (Arp and Manasc 1988, Matusiewicz and Barnes 1985), but it was not as dramatic as in our study.

Other Elements

None of the other elements analyzed in this study had significant trends. The data for these elements are available upon request to the senior author at College of Forest Resources, University of Washington, AR-10, Seattle, Washington 98195.

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